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Method for measurement of rotation rates/accelerations using a rotation rate Coriolis gyro, as well as a Coriolis gyro which is suitable for this purpose

5   The invention relates to a method for measurement of accelerations using a rotation rate Coriolis gyro, and to a Coriolis gyro which is suitable for this purpose.

Coriolis gyros (also referred to as vibration gyros)
10   are being increasingly used for navigation purposes; they have a mass system which is caused to oscillate. Each mass system generally has a large number of oscillation modes, which are initially independent of one another. In order to operate the Coriolis gyro, a
15   specific oscillation mode of the mass system is artificially excited, and this is referred to in the following text as the "excitation oscillation". When the Coriolis gyro is rotated, Coriolis forces occur which draw energy from the excitation oscillation of
20   the mass system and thus transmit a further oscillation mode of the mass system, which is referred to in the following text as the "read oscillation". In order to determine rotations of the Coriolis gyro, the read oscillation is tapped off and a corresponding read
25   signal is investigated to determine whether any changes have occurred in the amplitude of the read oscillation which represent a measure of the rotation of the Coriolis gyro. Coriolis gyros may be in the form of both an open-loop system and a closed-loop system. In a
30   closed-loop system, the amplitude of the read oscillation is continuously reset to a fixed value - preferably zero - via respective control loops, and the resetting forces are measured.

35   The mass system of the Coriolis gyro (which is also referred to in the following text as the "resonator") may in this case be designed in widely differing ways. For example, it is possible to use an integral mass system. Alternatively, it is possible to split the mass

system into two oscillators, which are coupled to one another via a spring system and can carry out relative movements with respect to one another. High dimensional accuracies can be achieved in particular with linear

5 double-oscillator systems, which comprise a coupled system composed of two linear oscillators. In double-oscillator systems, the spring system which couples the two linear oscillators to one another is in general designed in such a way that the two linear

10 oscillators can be caused to oscillate along a first oscillation axis, in which case the second oscillator can additionally carry out oscillations along a second oscillation axis, which is at right angles to the first oscillation axis. The movements of the second

15 oscillator along the second oscillation axis can in this case be regarded as a read oscillation, and the movements of the first and second oscillators along the first oscillation axis can be regarded as an excitation oscillation.

20

Linear double-oscillator systems have the disadvantage that the oscillations of the two linear oscillators along the first oscillation axis can cause vibrations or reflections in the gyro frame. In this case, the

25 "gyro frame" should be understood to be a mechanical, non-oscillating structure in which the oscillators are "embedded", for example a non-oscillating part of a silicon wafer. The vibrations or reflections in the gyro frame can in turn lead to disturbances (for

30 example damping effects) to the oscillator movements. For example the oscillations of the first and second linear oscillators along the first oscillation axis can thus be disturbed by external vibrations and accelerations which act along the first oscillation

35 axis. Analogously to this, external vibrations and accelerations which act in the direction of the second oscillation axis can disturb the oscillations of the second linear oscillator along this oscillation axis which - in precisely the same way as with all other

disturbance influences mentioned - leads to corruption of the measured rotation rate.

The object on which the invention is based is to specify a Coriolis gyro, by means of which any disturbance of the read oscillation, that is to say of the oscillation of the second linear oscillator in the direction of the second oscillation axis, as a result of the disturbance influences mentioned above can be largely avoided.

In order to achieve this object, the invention provides a Coriolis gyro as claimed in patent claim 1. Furthermore, the invention provides a method for measurement of accelerations/rotation rates using a rotation rate Coriolis gyro as claimed in patent claim 7. Advantageous refinements and developments of the idea of the invention can be found in the dependent claims.

The Coriolis gyro according to the invention has a first and a second resonator, which are each in the form of a coupled system comprising a first and a second linear oscillator, with the first resonator being mechanically/electrostatically connected/coupled to the second resonator such that the two resonators can be caused to oscillate in antiphase with respect to one another along a common oscillation axis.

Accordingly, the Coriolis gyro according to the invention has a mass system which comprises two double-oscillator systems (that is to say two resonators) or four linear oscillators. The antiphase oscillations of the two resonators with respect to one another in this case result in the center of gravity of the mass system remaining stationary, if the two resonators are designed appropriately. This results in the oscillation of the mass system not being able to produce any external vibrations which in turn would

result in disturbances in the form of damping/reflections. Furthermore, external vibrations and accelerations in the direction of the common oscillation axis have no influence on the antiphase movement of the two resonators along the common oscillation axis.

The first resonator can be coupled to the second resonator, for example via a spring system which connects the first resonator to the second resonator. A further possibility is to couple the first resonator to the second resonator via an electrostatic field. Both types of coupling may be used on their own or in conjunction. It is sufficient, for example, for both resonators to be formed in a common substrate so that the mechanical coupling is replaced by a mechanical connection, which is itself provided by the common substrate.

The configurations of the first and of the second resonator are preferably identical in terms of mass and shape. In this case, the two resonators may be arranged axially symmetrically with respect to one another with respect to an axis of symmetry which is at right angles to the common oscillation axis, that is to say the first resonator is mapped by the axis of symmetry onto the second resonator. However, the invention is not restricted to this and it is sufficient for the two resonators to have the same mass, but to be designed with different shapes.

As already mentioned, the coupled resonators are designed in such a way that both linear oscillators of a resonator can be caused to oscillate in antiphase along a first oscillation axis (excitation oscillation), and the second linear oscillator can additionally be caused to oscillate along a second oscillation axis (read oscillation). If the first and the second oscillation axes are at right angles to one

another, and both resonators are caused to oscillate in antiphase with respect to one another along the first oscillation axis (common oscillation axis), then the second oscillators are deflected in the opposite direction during rotation of the Coriolis gyro (antiphase deflection), while, in contrast, during acceleration of the Coriolis gyro, the second linear oscillators are deflected in the same direction (in-phase deflection). It is thus possible to selectively measure accelerations or rotations. The acceleration is measured by evaluation of an in-phase oscillation, and the rotation rate is measured by evaluation of an antiphase oscillation. In the following text, the expressions "in-phase" and "antiphase" have the following meanings: if the coordinates in the excitation direction are denoted x and those in the read direction are denoted y, then $x_1 = x_2$, $y_1 = y_2$ for in-phase oscillation and $x_1 = -x_2$, $y_1 = -y_2$ for antiphase oscillation (in this case, the index "1" denotes the first oscillator, and the index "2" the second oscillator).

For this reason, the invention provides a method for selective or simultaneous measurement of rotation rates and accelerations. This method uses a rotation rate Coriolis gyro which has a first and a second resonator which are each in the form of a coupled system comprising a first and a second linear oscillator, and in which rotation rates to be determined are determined by tapping and evaluation of the deflections of the second oscillators. The method has the following steps:
-    the two resonators are caused to carry out oscillations in antiphase with one another along a common oscillation axis,
-    the deflections of the second oscillators are compared with one another in order to determine an antiphase deflection component which is a measure of the rotation rate to be measured and/or in order to

determine a common in-phase deflection component, which is a measure of the acceleration to be measured, and
-    calculation of the rotation rate/acceleration to be   measured   from   the   in-phase   deflection
5   component/anti-phase deflection component.

The   common   in-phase   deflection   component   is advantageously   determined   as   follows: a   first quadrature bias which occurs within the first resonator
10   and a second quadrature bias which occurs within the second resonator are determined. The first and the second quadrature biases are then added and subtracted in   order   to   determine   a   common   quadrature   bias component   (in-phase   component)   and   a   difference
15   quadrature bias component (antiphase component). The common quadrature bias component is proportional to the acceleration to be measured, and corresponds to the common in-phase deflection component. The difference quadrature bias component (difference) corresponds to
20   the antiphase deflection component. The rotation rate can   thus   be   measured   at   the   same   time   as   the acceleration,   via   the   difference   quadrature   bias component.

25   In order to assist understanding of the acceleration measurement   principle   described   above,   the   physical principles of a Coriolis gyro will be explained briefly once   again   in   the   following   description,   using   the example of a linear double-oscillator system.
30

In general, Coriolis gyros have a quadrature bias, that is to say a zero error. The quadrature bias is in this case   composed   of   a   plurality   of   quadrature   bias components. One of these quadrature bias components
35   arises from alignment errors of the first and second linear   oscillator   with   respect   to   one   another,   with these   alignment   errors   being   unavoidable,   because   of manufacturing tolerances. The alignment errors between

the two oscillators produce a zero error in the measured rotation rate signal.

The Coriolis force can be represented as:

$$\vec{F} = 2m\vec{v}_s x \vec{\Omega} \qquad\qquad [1]$$

$\vec{F}$ Coriolis force
m Mass of the oscillator
$\vec{v}_s$ Velocity of the oscillator
$\vec{\Omega}$ Rotation rate

If the mass which reacts to the Coriolis force is equal to the oscillating mass, and if the oscillator is operated at the natural frequency □, then:

$$2m\vec{v}_s x \vec{\Omega} = m\vec{a}_c \qquad\qquad [2]$$

The oscillator velocity is given by:

$$\vec{v}_s = \vec{v}_{s0} \sin \omega t \qquad\qquad [3]$$

where
$\vec{v}_{s0}$ oscillator amplitude
ω natural frequency of the oscillator

The oscillator and Coriolis accelerations are thus given by:

$$\vec{a}_s = \vec{v}_{s0} \omega \cos \omega t$$
$$\vec{a}_c = 2\vec{v}_{s0} \sin \omega t \times \vec{\Omega} \qquad\qquad [4]$$

The two acceleration vectors are thus spatially at right angles to one another and are offset through 90° with respect to one another in the time function (spatial and time orthogonality).

These two criteria can be used in order to separate the oscillator acceleration $\vec{a}_s$ from the Coriolis

acceleration $\vec{a}_c$. The ratio of the abovementioned acceleration amplitudes a_c and a_s is:

$$\frac{a_c}{a_s} = \frac{2\Omega}{\omega} \qquad\qquad [5]$$

If the rotation rate is $\Omega = 5°/h$ and the natural frequency of the oscillator is $f_s = 10$ KHz, then:

$$\frac{a_c}{a_s} = 7.7 \cdot 10^{-10} \qquad\qquad [6]$$

For an accuracy of 5°/h, undesirable couplings of the first oscillator to the second oscillator must not exceed $7.7 \cdot 10^{-10}$, or must be constant at this value. If a mass system composed of two linear oscillators is used, which are coupled to one another via spring elements, then the accuracy of the spatial orthogonality is limited because of the alignment error of the spring elements between the oscillation mode and the measurement mode. The achievable accuracy (limited by manufacturing tolerances) is 10^{-3} to 10^{-4}. The accuracy of the time orthogonality is limited by the phase accuracy of the electronics at, for example, 10 KHz, which can likewise be complied with only to at most 10^{-3} to 10^{-4}. This means that the ratio of the accelerations as defined above cannot be satisfied.

Realistically, the resultant error in the measured acceleration ratio a_c/a_s is:

$$\frac{a_c}{a_s} = 10^{-6} \, to \, 10^{-8} \qquad\qquad [7]$$

The spatial error results in a so-called quadrature bias B_Q, which, together with the time phase error $\square_\square$, results in a bias B:

$$B_Q = 6.5 \cdot 10^6 \, °/h \text{ to } 6.5 \cdot 10^5 \, °/h$$

$\square_\square=10^{-3}$ to 10^{-4}

$B=B_Q\cdot\square_\square=6,500$ °/h to 65 °/h   [8]

The quadrature bias thus results in a major restriction
to the measurement accuracy. In this case, it should be
noted that the above error analysis takes account only
of the direct coupling of the oscillation mode to the
read mode. Further quadrature bias components also
exist and occur, for example, as a result of couplings
with other oscillation modes.

If the Coriolis gyro is designed in such a way that the
first oscillators are connected by first spring
elements to a gyro frame of the Coriolis gyro, and the
second oscillators are connected by second spring
elements to in each case one of the first oscillators,
then the acceleration to be measured results in a
change in the mutual alignment of the first oscillators
with respect to the second oscillators, and this is
manifested in particular in a change in the alignment
of the second spring elements. The alignment change of
the second spring elements in this case produces an
"artificial" quadrature bias component, that is to say
an "error" in the quadrature bias signal. It is thus
also indirectly possible to use the determination of
the quadrature bias to deduce the acceleration to be
measured, which produces the corresponding "artificial"
quadrature bias component.

The alignments of the first and second spring elements
are preferably at right angles to one another. The
spring elements may have any desired shape.

The expression "first quadrature bias" and "second
quadrature bias" in each case preferably mean the total
quadrature bias of a resonator. However, it is also
possible in the acceleration measurement method
according to the invention to in each case determine
only one quadrature bias component in each resonator,

in which case the determined quadrature bias component must include at least that component which is produced by the acceleration to be measured or the rotation to be measured.

The Coriolis gyro preferably has a device for determination of first rotation rate and quadrature bias signals which occur within the first resonator, and second rotation rate and quadrature bias signals which occur within the second resonator. Furthermore, the Coriolis gyro may have a device for production of electrostatic fields, by means of which the alignment angle of the first spring elements with respect to the gyro frame can be varied and/or the alignment angle of the second spring elements with respect to the first oscillators can be varied. The alignment/strength of the electrostatic fields can then be regulated by provision of appropriate control loops, such that the first and the second quadrature bias are in each case as small as possible. A computation unit can use the first and second rotation rate/quadrature bias signals to determine the rotation rate, and can use an in-phase component of the electrostatic fields which compensate for the first and second quadrature biases, to deduce the acceleration to be measured.

The quadrature bias is thus preferably eliminated at its point of origin itself, that is to say mechanical alignment errors of the two oscillators with respect to one another and changes in the mutual alignment of the two oscillators caused by the acceleration/rotation to be measured are compensated for by means of an electrostatic force which acts on one or both oscillators and is produced by the electrostatic field. This type of quadrature bias compensation has the advantage that both rotation rates and accelerations can be determined with increased measurement accuracy.

In one particularly preferred embodiment, the electrical fields change the alignment angles of the first and second spring elements in order to make the alignments of the first and second spring elements orthogonal with respect to one another. Orthogonalization such as this results in compensation for the quadrature bias (component) produced in this way. Further contributions to the quadrature bias are used to set the error angle with respect to orthogonality such that the overall quadrature bias disappears. The alignment angles of the second spring elements with respect to the first oscillator are preferably varied by means of the electrostatic field, and the alignment angles of the first spring elements with respect to the gyro frame of the Coriolis gyro are not changed. However, it is also possible to use the electrostatic field to vary only the alignment angles of the first spring elements, or to vary the alignment angles of both the first and the second spring elements.

One particularly preferred embodiment of a Coriolis gyro according to the invention has:

- an ("overall") resonator, which is in the form of a system comprising two coupled first (linear) oscillators ("sub-resonators") which are excited in antiphase and each contain a second linear read oscillator,
- a device for production of at least one electrostatic field, by means of which the alignment of the two coupled first oscillators with respect to the second (read) oscillators can be varied,
- a device for determination of the quadrature biases of the read oscillators which are caused by alignment errors of the two oscillators with respect to the excitation oscillator and further coupling mechanisms,
- a control loop which in each case regulates the intensity of the at least one electrostatic field by

means of at least one corresponding control signal such that the determined quadrature biases are as small as possible,

- a computation unit, which in each case forms differences and sums of the at least one control signal and uses them to determine the rotation rate and the acceleration.

In principle, it is possible to calculate accelerations and rotation rates just on the basis of the determined quadrature biases, that is to say it is not absolutely essential to compensate for the first and second quadrature bias in order to determine the quadrature biases. However, this is advisable for measurement accuracy reasons, since phase tolerances result in the rotation rate and the quadrature being mixed with one another. The invention covers both alternatives.

It has also been found to be advantageous for each of the second oscillators to be attached to or clamped in on the first oscillator "at one end" in the resonators. "Clamped in at one end" can in this case be understood not only in the sense of the literal wording but also in a general sense. In general, attached or clamped in "at one end" means that the force is introduced from the first oscillator to the second oscillator essentially from one "side" of the first oscillator. If, by way of example, the oscillator system were to be designed in such a way that the second oscillator is bordered by the first oscillator and is connected to it by means of second spring elements, then the expression "clamped in or attached at one end" would imply the following: the second oscillator is readjusted for the movement by the first oscillator, by the first oscillator alternately "pushing" or "pulling" the second oscillator by means of the second spring elements.

Clamping the second oscillator in at one end on the
first oscillator has the advantage that, when an
electrostatic force is exerted on the second oscillator
as a result of the alignment/position change of the
5   second oscillator which results from this, the second
spring elements can be slightly curved, thus making it
possible, without any problems, to vary the
corresponding alignment angle of the second spring
elements. If the second oscillator in this example were
10   to be attached to additional second spring elements in
such a way that, during movement of the first
oscillator, the second oscillator were at the same time
to be "pulled" and "pushed" by the second spring
elements, then this would be equivalent to the second
15   oscillator being clamped in or attached "at two ends"
to the first oscillator (with the force being
introduced to the second oscillator from two opposite
ends of the first oscillator). In this case, the
additional second spring elements would produce
20   corresponding opposing forces when an electrostatic
field is applied, so that changes in the alignment
angles of the second spring elements could be achieved
only with difficulty. However, clamping in at two ends
is acceptable when the additional second spring
25   elements are designed such that the influence of these
spring elements is small so that all of the spring
elements can bend without any problems in this case as
well, that is to say the clamping in is effectively at
one end. Depending on the design of the oscillator
30   structure, clamping in at one end can effectively be
provided just by the "influence" (force introduction)
of the additional second spring elements being 40% or
less. However, this value does not present any
restriction to the invention, and it is also feasible
35   for the influence of the second spring elements to be
more than 40%. By way of example, clamping in at one
end can be achieved by all of the second spring
elements which connect the second oscillator to the
first oscillator being arranged parallel and on the

same plane as one another. All start and end points of the second spring elements are in each case attached to the same ends of the first and second oscillator. The start and end points of the second spring elements may in this case advantageously each be on a common axis, with the axes intersecting the second spring elements at right angles.

If the second oscillator is attached to or clamped on the first oscillator at one end, then the first spring elements are preferably designed such that they clamp the first oscillator in on the gyro frame at two ends (the expressions "at one end" and "at two ends" can be used analogously here). As an alternative to this, however, it is possible for the spring elements also to be designed in such a way that they clamp in the first oscillator at one end. By way of example, all the first spring elements which connect the first oscillator to the gyro frame of the Coriolis gyro can be arranged parallel and on the same plane as one another, with the start and end points of the first spring elements in each case preferably being located on a common axis. It is equally possible for the spring elements to be designed in such a way that the first oscillator is clamped in on the gyro frame at one end, and the second oscillator is clamped in at two ends by the first oscillator. It is also possible for both oscillators to be clamped in at two ends. For quadrature bias compensation, it has been found to be advantageous for at least one of the two oscillators to be clamped in at one end.

The invention will be explained in more detail in the following text with reference to one exemplary embodiment in the figures, in which:

Figure 1 shows one possible embodiment of a mass system, which comprises two linear oscillators, with corresponding control loops

which are used to excite the first oscillator.

Figure 2   shows one possible embodiment of a mass
            system which comprises two linear oscillators
            with corresponding measurement and control
            loops for a rotation rate Ω and a quadrature
            bias B_Q, as well as auxiliary control loops
            for compensation of the quadrature bias B_Q.

Figure 3   shows an outline sketch of a mass system
            according to the invention, which comprises
            four linear oscillators, with corresponding
            measurement and control loops for a rotation
            rate Ω and a quadrature bias B_Q, as well as
            the auxiliary control loops for compensation
            of the quadrature bias.

Figure 4   shows one preferred embodiment of the control
            system shown in Figure 3.

Figure 1 shows the schematic design of a linear double
oscillator 1 with corresponding electrodes, as well as
a block diagram of associated evaluation/excitation
electronics 2. The linear double oscillator 1 is
preferably produced by means of etching processes from
a silicon wafer, and has a first linear oscillator 3, a
second linear oscillator 4, first spring elements 5_1 to
5_4, second spring elements 6_1 and 6_2 as well as parts of
an intermediate frame 7_1 and 7_2 and of a gyro frame 7_3
and 7_4. The second oscillator 4 is mounted within the
first oscillator 3 such that it can oscillate, and is
connected to it via the second spring elements 6_1, 6_2.
The first oscillator 3 is connected to the gyro frame
7_3, 7_4 by means of the first spring elements 5_1 to 5_4
and the intermediate frame 7_1, 7_2.

Furthermore, first excitation electrodes 8_1 to 8_4, first
read electrodes 9_1 to 9_4, second excitation electrodes

10_1 to 10_4, and second read electrodes 11_1 and 11_2 are provided. All of the electrodes are mechanically connected to the gyro frame, but are electrically isolated. The expression "gyro frame" means a mechanical, non-oscillating structure in which the oscillators are "embedded", for example the non-oscillating part of the silicon wafer.

If the first oscillator 3 is excited by means of the first excitation electrodes 8_1 to 8_4 to oscillate in the X1 direction, then this movement is transmitted through the second spring elements 6_1, 6_2 to the second oscillator 4 (alternate "pulling" and "pushing"). The vertical alignment of the first spring elements 5_1 to 5_4 prevents the first oscillator 3 from moving in the X2 direction. However, a vertical oscillation can be carried out by the second oscillator 4 as a result of the horizontal alignment of the second spring elements 6_1, 6_2. When corresponding Coriolis forces accordingly occur, then the second oscillator 4 is excited to oscillate in the X2 direction.

A read signal which is read from the first read electrodes 9_1 to 9_4 and is proportional to the amplitude/frequency of the X1 movement of the first oscillator 3 is supplied via appropriate amplifier elements 21, 22 and 23 to an analog/digital converter 24. An appropriately digitized output signal from the analog/digital converter 24 is demodulated not only by a first demodulator 25 but also by a second demodulator 26 to form corresponding output signals, with the two demodulators operating with an offset of 90° with respect to one another. The output signal from the first demodulator 25 is supplied to a first regulator 27 in order to regulate the frequency of the excitation oscillation (the oscillation of the mass system 1 in the X1 direction), whose output signal controls a frequency generator 30 such that the signal which occurs downstream from the demodulator 25 is regulated

at zero. Analogously to this, the output signal from the second demodulator 26 is regulated at a constant value, which is predetermined by the electronics component 29. A second regulator 31 ensures that the amplitude of the excitation oscillation is regulated. The output signals from the frequency generator 30 and from the amplitude regulator 31 are multiplied by one another, by means of a multiplier 32. An output signal from the multiplier 32, which is proportional to the force to be applied to the first excitation electrodes 8_1 to 8_4 acts not only on a first force/voltage converter 33 but also a second force/voltage converter 34, which use the digital force signal to produce digital voltage signals. The digital output signals from the force/voltage converters 33, 34 are converted via a first and a second digital/analog converter 35, 36 to corresponding analog voltage signals, which are then passed to the first excitation electrodes 8_1 to 8_4. The first regulator 27 and the second regulator 31 readjust the natural frequency of the first oscillator 3, and set the amplitude of the excitation oscillation to a specific, predeterminable value.

When Coriolis forces occur, the movement of the second oscillator 4 in the X2 direction (read oscillation) that results from this is detected by the second read electrodes 11_1, 11_2, and a read signal which is proportional to the movement of the read oscillation is supplied via appropriate amplifier elements 40, 41 and 42 to an analog/digital converter 43 (see Figure 2). A digital output signal from the analog/digital converter 43 is demodulated by a third demodulator 44 in phase with the direct-bias signal, and is demodulated by a fourth demodulator 45, offset through 90°. A corresponding output signal from the first demodulator 44 is applied to a third regulator 46, whose output signal is a compensation signal and corresponds to the rotation rate Ω to be measured. An output signal from the fourth demodulator 45 is applied to a fourth

regulator 47, whose output signal is a compensation signal and is proportional to the quadrature bias to be compensated for. The output signal from the third regulator is modulated by means of a first modulator

5   48, and the output signal from the fourth regulator 47 is modulated in an analogous manner to this by means of a second modulator 49, so that amplitude-regulated signals are produced whose frequencies correspond to the natural frequency of the oscillation in the X1

10 direction (sin $\cong$ 0°, cos $\cong$ 90°). Corresponding output signals from the modulators 48, 49 are added in an addition stage 50, whose output signal is supplied both to a third force/voltage converter 51 and to a fourth force/voltage converter 52. The corresponding output

15 signals for the force/voltage converters 51, 52 are supplied to digital/analog converters 53, 54, whose analog output signals are applied to the second excitation electrodes 10_2 to 10_3, and reset the oscillation amplitudes of the second oscillator 4.

20

The electrostatic field which is produced by the second excitation electrodes 10_1 and 10_4 (or the two electrostatic fields which are produced by the electrode pairs 10_1, 10_3 and 10_2, 10_4) results in an

25 alignment/position change of the second oscillator 4 in the X2 direction, and thus in a change in the alignments of the second spring elements 6_1 to 6_2. The fourth regulator 47 regulates the signal which is applied to the second excitation electrodes 10_1 and 10_4

30 in such a way that the quadrature bias which is included in the compensation signal of the fourth regulator 47 is as small as possible, or disappears. A fifth regulator 55, a fifth and a sixth force/voltage converter 56, 57 and two analog/digital converters 58,

35 59 are used for this purpose.

The output signal from the fourth regulator 47, which is a measure of the quadrature bias, is supplied to the fifth regulator 55, which regulates the electrostatic

field that is produced by the two excitation electrodes 10_1 and 10_4 in such a way that the quadrature bias B_Q disappears. For this purpose, an output signal from the fifth regulator 55 is in each case supplied to the

5 fifth and sixth force/voltage converters 56, 57, which use the digital force/output signal from the fifth regulator to produce digital voltage signals. These are then converted to analog voltage signals in the analog/digital converters 58, 59. The analog output

10 signal from the analog/digital converter 58 is supplied to the second excitation electrode 10_1 or alternatively 11_1. The analog output signal from the analog/digital converter 59 is supplied to the second excitation electrode 10_4, or alternatively 11_2.

15

Since the second oscillator 4 is clamped in only by the second spring elements 6_1 to 6_2 (clamping in at one end), the alignment of these spring elements can be varied without any problems by the electrostatic field.

20 It is also possible to provide additional second spring elements, which result in the second oscillator 4 being clamped in at two ends, provided that these additional spring elements are designed appropriately to ensure that clamping in at one end is effectively achieved. In

25 order to allow the same effect for the spring elements 5_1, 5_2 and the spring elements 5_3, 5_4 as well, the third and fourth spring elements 5_3, 5_4 and the first and second spring elements 5_1, 5_2 may be omitted, thus resulting in the first oscillator 3 being clamped in at

30 one end (together with an appropriately modified electrode configuration, which is not shown here). In a situation such as this, the second oscillator 4 could also be attached to the first oscillator by means of further spring elements in order to achieve clamping in

35 at two ends.

One preferred embodiment of the Coriolis gyro according to the invention and its method of operation will be

described in more detail in the following description with reference to Figure 3.

Figure 3 shows the schematic layout of coupled system 1' comprising a first resonator 70_1 and a second resonator 70_2. The first resonator 70_1 is coupled to the second resonator 70_2 via a mechanical coupling element 71, a spring. The first and the second resonator 70_1, 70_2 are formed in a common substrate and can be caused to oscillate in antiphase with respect to one another along a common oscillation axis 72. The first and the second resonator 70_1, 70_2 are identical, and are mapped onto one another via an axis of symmetry 73. The design of the first and of the second resonator 70_1, 70_2 has already been explained in conjunction with Figures 1 and 2, and will therefore not be explained again; identical and mutually corresponding components or component groups are identified by the same reference numbers with identical components which are associated with different resonators being identified by different indices.

One major difference between the double oscillators shown in Figure 3 and the double oscillators shown in Figures 1 and 2 is that some of the individual electrodes are physically combined to form one overall electrode. For example, the individual electrodes which are identified by the reference numbers 8_1, 8_2, 9_1 and 9_2 in Figure 3 thus form a common electrode. Furthermore, the individual electrodes which are identified by the reference numbers 8_3, 8_4, 9_3 and 9_4 form a common electrode, and those with the reference numbers 10_4, 10_2, 11_2 as well as the reference numbers 11_1, 10_3 and 10_1 each form an overall electrode. The same applies in an analogous manner to the other double-oscillator system.

During operation of the coupled system 1' according to the invention, the two resonators 70_1, 70_2 oscillate in

antiphase along the common oscillation axis 72. The coupled system 1' is thus not susceptible to external disturbances or to disturbances which are emitted by the coupled system 1' itself into the substrate in
5 which the resonators 70_1 and 70_2 are mounted.

When the coupled system 1' is rotated, then the second oscillators 4_1 and 4_2 are deflected in mutually opposite directions (in the X2 direction and in the opposite
10 direction to the X2 direction). When an acceleration of the coupled system 1' occurs, then the second oscillators 4_1, 4_2 are each deflected in the same direction, specifically in the same direction as the acceleration, provided that this acceleration is in the
15 X2 direction, or in the opposite direction to it. Accelerations and rotations can thus be measured simultaneously or selectively. Quadrature bias compensation can be carried out at the same time during the measurement process, in the resonators 70_1, 70_2.
20 However, this is not absolutely essential.

In principle, it is possible to operate the coupled system 1' on the basis of the evaluation/excitation electronics 2 described in Figures 1 and 2. However, an
25 alternative method (carrier frequency method) is used instead of this in the embodiment shown in Figure 3. This operating method will be described in the following text.

30 The evaluation/excitation electronics 2 which are identified by the reference number 2' have three control loops: a first control loop for excitation and/or control of an antiphase oscillation of the first oscillators 3_1 and 3_2 along the common oscillation axis
35 72, a second control loop for resetting and compensation of the oscillations of the second oscillator 4_1 along the X2 direction, and a control loop for resetting and compensation of the oscillations of the second oscillator 4_2 along the X2 direction. The

three described control loops have an amplifier 60, an analog/digital converter 61, a signal separation module 62, a first to third demodulation module 63_1 to 63_3, a control module 64, an electrode voltage calculation
5   module 65, a carrier frequency addition module 67, and a first to sixth digital/analog converter 66_1 to 66_6.

Carrier frequencies can be applied to the electrodes 8_1 to 8_8, 9_1 to 9_8, 10_1 to 10_8 and 11_1 to 11_4 for tapping
10 excitation of the antiphase oscillation or of the oscillations of the second oscillators 4_1, 4_2, in a number of ways: a) using three different frequencies, with one frequency being associated with each control loop, b) using square-wave signals with a time-division
15 multiplexing method, or c) using random phase scrambling (stochastic modulation method). The carrier frequencies are applied to the electrodes 8_1 to 8_8, 9_1 to 9_8, 10_1 to 10_8 and 11_1 to 11_4 via the associated signals UyAo, UyAu (for the second oscillator 4_1) and
20 Uxl, Uxr (for the antiphase resonance of the first oscillators 3_1 to 3_2) as well as UyBu and UyBo (for the second oscillator 4_2), which are produced in the carrier frequency addition module 67 and are excited in antiphase with respect to the abovementioned frequency
25 signals. The oscillations of the first and second oscillators 3_1, 3_2, 4_1 and 4_2 are tapped off via those parts of the gyro frame which are identified by the reference numbers 7_7, 7_9, 7_{11} and 7_{13}, and in this case are additionally used as tapping electrodes, in
30 addition to their function as suspension points for the mass system. For this purpose, the two resonators 70_1, 70_2 are preferably and advantageously designed to be electrically conductive, with all of the frames, springs and connections. The signal which is tapped off
35 by means of the gyro frame parts 7_7, 7_9, 7_{11} and 7_{13} and is supplied to the amplifier 60 contains information about all three oscillation modes, and is converted by the analog/digital converter 61 to a digital signal which is supplied to the signal separation module 62.

The assembled signal is separated in the signal separation module 62 into three different signals: x (which contains information about the antiphase oscillation), yA (which contains information about the deflection of the second oscillator 4_1), as well as yB (which contains information about the deflection of the second oscillator 4_2). The signals are separated differently depending on the type of carrier frequency method used (see a) to c) above), and separation is carried out by demodulation with the corresponding signals of the carrier frequency method that is used. The signals x, yA and yB are supplied to the demodulation modules 63_1 to 63_3, which demodulate them using an operating frequency of the antiphase oscillation for 0° and 90°. The control module 64 as well as the electrode voltage calculation module 65 for regulation/calculation of the signals Fxl/r or Uxl/r, respectively are preferably configured analogously to the electronics module 2 shown in Figure 1. The control module 64 and the electrode voltage calculation module 65 for regulation/calculation of the signals FyAo/u, UyAo/u, and FyBo/u, UyBo/u are preferably designed analogously to the electronics module 2 shown in Figure 2.

Figure 4 shows one preferred embodiment of the control system that is identified by the reference number 64 in Figure 3. The control system 64 has a first to third part 64_1 to 64_3. The first part 64_1 has a first regulator 80, a frequency generator 81, a second regulator 82, an electronics component 83, an addition stage 84 and a multiplier 85. The method of operation of the first part corresponds essentially to the method of operation of the electronics module 2 shown in Figure 1, and will therefore not be described once again here. The second part 64_2 has a first regulator 90, a first modulator 91, a second regulator 92, a second modulator 93 and a third regulator 94. A first and a second addition stage 95, 96 are also provided. A

rotation rate signal Ω can be determined at the output of the first regulator 90, and an assembled signal comprising a quadrature bias B_Q and an acceleration A can be determined at the output of the third regulator
5   94. The third part 64_3 of the control system 64 has a first regulator 100, a first modulator 101, a second regulator 102, a second modulator 103 and a third regulator 104. A first and a second addition stage 105, 106 are also provided. A rotation rate signal Ω with a
10   negative mathematical sign can be tapped off at the output of the first regulator 100, and an assembled signal comprising the quadrature bias B_Q with a negative mathematical sign and an acceleration signal A can be tapped off at the output of the third regulator
15   104. The method of operation of the second and of the third part 64_2 and 64_3 corresponds to that of the electronics module 2 illustrated in Figure 2, and will therefore not be explained once again here.

20   Only the signals for resetting of the rotation rate and the quadrature after the multiplication by the operating frequency are passed together with the DC voltages for the quadrature auxiliary regulator to a combined electrode pair. The two signals are therefore
25   added, so that the calculation of the electrode voltages includes the reset signals for the oscillation frequency and the DC signal for quadrature regulation. The electrode voltages Uxl/r, UyAo/u and UyBo/u calculated in this way are then added to the carrier
30   frequency signals, and are passed jointly via the analog/digital converters 66_1 to 66_6 to the electrodes.

The carrier frequency methods described above with antiphase excitation have the advantage that a signal
35   is applied to the amplifier 60 only when the linear oscillators 3_1, 3_2 as well as 4_1 and 4_2 are deflected. The frequency signals which are used for excitation may be discrete frequencies or square-wave signals.

Square-wave excitation is preferred, as it is easier to produce and process.

A number of analyses relating to the measurement
accuracy of the acceleration measurement method
according to the invention will also be described in
the following text.

The rotation rate results in an antiphase deflection of
the oscillators 4_1 and 4_2 at the operating frequency of
the Coriolis gyro; in contrast, acceleration results in
an in-phase deflection of the oscillators 4_1 and 4_2, in
which case the acceleration can be measured in the
frequency range from 0 Hz to about 500 Hz with a
measurement accuracy of 50 mg to 50 $\overline{g}$.

The in-phase deflection to be measured is given by:

$$\square = \frac{a}{\ell \cdot \omega^2}$$

$\square$ Deflection angle

a   Acceleration

$\square$ Length of the spring

$\square$ Natural frequency of the oscillators 4_1 to 4_2.

For typical natural frequencies $\square = 2 * \boxplus = 6000$ rad/s
to 60000 rad/s and spring lengths of $\square = 1$ mm of
Coriolis gyros, the measurement accuracy of, for
example 5 mg is:

$\square = 1.4*10^{-6}$ to $1.4*10^{-8}$ rad or $x_2=x_{\square}=1.4$ nm to 14 pm.

Small deflections such as these are difficult to
measure in the frequency range from 0 to 500 Hz. At the
least, this requires additional electronic complexity
for the multisensor according to the invention, because
the electronics have to measure very accurately both in
the operating range of the gyro function (rotation rate
measurement) from 1 to 10 KHz and in the operating

range for measurement of the acceleration from 0 to 500 Hz.

This disadvantage can be overcome according to the
5   invention by using the quadrature regulation, as described above, for a mass system comprising two linear oscillators (Figures 1 and 2) for the mass system composed of four linear oscillators (Figure 3): the acceleration detunes the orthogonality error, thus
10   resulting in an in-phase quadrature signal, which can clearly be seen, at the operating frequency in the oscillators 4_1 and 4_2:

$$\Omega_Q = \frac{a_Q}{a_s} \cdot \frac{\omega}{2} = \alpha \frac{\omega}{2}$$

15

In this case, Ω_Q is the quadrature rotation rate, a_Q is the quadrature acceleration and a_s is the oscillator acceleration.

20   For a measurement accuracy of, for example 5 mg ($\square = 1.4.10^{-6}$ rad), this results in:

$$\Omega_Q = 0.0042 \frac{rad}{s} = 0.25°/s = 866°/h \quad\quad \text{at a natural}$$

frequency of 1 kHz

25   $$\Omega_Q = 4.2 \cdot 10^{-5} \frac{rad}{s} /0.0025°/s = 8.7°/h \quad \text{at a natural}$$

frequency of 10 kHz

For a rotation rate sensor of 5°/h, the quadrature rotation rate of 866°/h can be verified with certainty
30   using the same electronics while, in contrast, at the natural frequency of 10 KHz and with the quadrature rotation rate of 8.7°/h, the verification limit of the rotation rate sensor of 5°/h is virtually exhausted. Although this measurement is also stable in the long
35   term, it depends on the long-term stability of the quadrature rotation rate. The actual quadrature rotation rate is an antiphase signal. The stability of

the acceleration measurement therefore depends on the difference in the quadrature rotation rates from the oscillator 4_1 to the oscillator 4_2, and their stability. Since the two oscillators are located close to one another and were manufactured in one process step, it is predicted that it is possible to cover a range with low accuracy from 50 mg to 50 g.